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The update of the European strategy for particle physics

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Abstract
This paper describes the process which led to the update of the European strategy for particle physics in 2013. A large number of proposals for new facilities and projects were submitted to the Strategy Group and their physics potential and technological feasibility were carefully analyzed. An overview of these projects is given, followed by a summary of the main points of the approved European Strategy Update. The official text, which was approved at a special session of the CERN Council in 30 May 2013 is reproduced in the appendix.

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1. The European strategy defined in 2006

In June 2005 CERN Council decided to set up a scientific advisory group, the so-called Strategy Group, to propose a strategy for European particle physics in the decade to come. This strategy should address the main lines of particle physics in Europe, accelerator-based and non-accelerator based, including R&D for novel accelerators and detector technologies. The Strategy Group organized a bottom-up process involving the whole European particle physics community. The key phases of this process were an open symposium in Orsay in January 2006 and a Strategy Group meeting in Zeuthen, in March 2006. This first European strategy for particle physics was finally unanimously approved by the CERN Council at a special session held in Lisbon on 14 July 2006. Relevant documents concerning the work of the Strategy Group are available at http://cern.ch/council-strategygroup/. The strategy document contains 17 statements on scientific and organizational matter.

The strategy in 2006 was defined at a time when the Large Hadron Collider (LHC) was still in construction. From the physics point of view no hint for the existence of a Higgs particle was available from the Tevatron, nor was there any prediction for a possible energy scale of interest for a Linear Collider. The obvious outcome of the strategy discussion was to place the completion of the LHC machine as the highest priority. The strategy then encouraged the carrying out of R&D on a list of essential projects with the aim to achieve an engineering readiness when physics results became available and a decision had to be made. These R&D projects include work to develop the compact linear collider (CLIC) technology and high performance magnets for future accelerators, the design and technical preparation for electron–positron collider (ILC), and the participation in a global neutrino program. The strategy in 2006 also foresaw an update of the European strategy. For this purpose a dedicated body will be established.

2. The update process

The process to update the European strategy for particle physics was initiated by the CERN Council with the establishment of the Strategy Group in 2011. It was composed of representatives from each CERN member state and of the directors of the major European laboratories. The update was coordinated by the strategy secretariat consists of the Scientific Secretary, the chairpersons of the CERN Scientific Policy Committee (SPC) and the European Committee for Future Accelerators (ECFA), the representative of the European laboratory directors, and a Scientific Assistant. Invited to attend the meetings of the Strategy Group are representatives from the candidates for accession and associate member states, from observer states, the director of JINR, Dubna, as well as representatives from EU, APPEC[1], and the chairpersons from FALC[2], ESFRI[3] and NuPECC[4].

[1] AstroParticle Physics European Consortium.
[2] Funding Agencies for Large Colliders.
[3] European Strategy Forum on Research Infrastructures.
[4] Nuclear Physics European Collaboration Committee.

In addition a Preparatory Group was established. The group's task was to prepare the background material for the Strategy Group and to organize an open symposium and the drafting session. The Preparatory Group consists of eight members drawn from ECFA and SPC, the scientific secretary, and one representative from Asia and one from the Americas.

Following a call for scientific input from the particle physics community in February 2012 about 160 contributions were submitted by individuals, collaborations, national institutes and countries. In September 2012 an open symposium was held in Krakow (http://espp2012.ifj.edu.pl), which was attended by close to 500 participants. Using all the information from the written contributions and the presentations and discussions during the open symposium the Preparatory Group produced the Scientific Briefing Book (http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/Briefing_book.pdf).

Parallel to the discussions on scientific issues, five working groups were set up to discuss organizational and other mattes. These working groups were:

- WG1—organizational structure for the Council for the European strategy and its implementation.
- WG2—organizational structure for European participation in global projects, role and definition of the national laboratories and the CERN laboratory in the European strategy.
- WG3—relations with external bodies, in particular EU-related.
- WG4—knowledge and technology transfer, and relations with industry.
- WG5—communication, outreach and education.

In January 2013 the Strategy Group met in Erice for the drafting session. After extensive discussions a draft of the Update of the European Strategy for particle physics was agreed and submitted to CERN Council. During the CERN Council meeting in March, Council agreed on the final draft with minor wording amendments. The Update of the European Strategy was formally adopted at a special session of Council in Brussels 30 May 2013. The official text of the Strategy Update is reproduced in the appendix.

3. Proposed facilities and projects

The year 2012 was an exciting one for fundamental physics. Not only a new particle was discovered, which appeared to have the properties of the long sought-after Higgs boson, also the third neutrino mixing angle θ_{13} was discovered to be large. Especially the relatively low mass of the new boson of about 125 GeV/c^{-2} triggered the imagination of physicists to propose facilities for the study of this new particle in great detail. This section gives an overview of the plurality of accelerator facilities that have been proposed to the Strategy Group with the aim to perform physics experiments at highest possible energies and very high intensities. One should note, however, that the proposed facilities are in very different stages of development—from very detailed design reports to short written inputs to the Strategy Group.

3.1. Hadron colliders

At the moment the LHC is the hadron collider at the energy forefront. The time line for the operation of the LHC including the option for a significant increase in intensity (HL-LHC) has been discussed in terms of its physics reach and technical challenges. Beyond LHC, hadron colliders may remain the route to a further increase of the collision energy. Possible future hadron colliders are the energy-doubler of the LHC (HE-LHC) or colliders with larger circumferences than the LHC (V-LHC). For an overview of the main accelerator parameters of proposed hadron colliders see table 1.

3.1.1. LHC high luminosity upgrade. HL-LHC is proposed to be operated in the period of about 2023–2030 at 14 TeV with a luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ using the concept of luminosity leveling. The goal of HL-LHC is to deliver 3000 fb^{-1} to both ATLAS and CMS. A series of improvements and upgrades to the machine are required to reach the proposed high luminosity. One should note, however, that some of these measures are needed in any case to guaranty the operation of the LHC and the experiments even at the present luminosity. By exchanging aged parts with improved components (performance-improving consolidation) parts of the upgrade are done gradually. An example for this is the exchange of the final focusing magnets.

3.1.2. High energy LHC. A consideration to further exploit the CERN complex of accelerators beyond HL-LHC is to install dipole magnets with higher fields in the existing LHC tunnel. Such a machine, called high-energy LHC (HE-LHC) could reach a center-of-mass energy of 26–33 TeV. The beam energy is set by the strength of the achievable dipole field of the superconducting magnets. Using the classical low temperature superconductor, Nb_3Sn, a dipole field of 16 T is feasible resulting in a collision energy of 26 TeV. A possible design of a 20 T HE-LHC magnet employing high temperature superconductors in the inner part of the dipole magnets, such as YBCO-123 or BSCCO-2212, is studied. With this magnet design a target beam energy of 16.5 TeV seams feasible, resulting in a center of mass energy of 33 TeV. The design luminosity of such a machine is $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Assuming that a decision on the use of high temperature superconductors is made in 2016–2017, followed by 3 years of prototyping, 7 years of industrialization, construction and testing, and finally 3 years of installation and commissioning after the termination of HL-LHC, physics production could start around 2035.

3.1.3. Very large hadron collider. A geological pre-feasibility study was done to examine possible new tunnels of up to 80 km within the Geneva area for the hosting of a very large hadron collider (V-LHC) [1]. With the present LHC magnet technology with 8.3 T an energy of 42 TeV could be reached in an 80 km tunnel. Using Nb_3Sn magnets or additionally high temperature superconductors a dipole field of 16 or 20 T may be achieved resulting in an envisaged collision energy of 80 or 100 TeV, respectively.

Table 1. Overview of proposed proton–proton colliders.

Facility	Years	E_{cm} (TeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Int. luminosity (fb^{-1})	Comments
Design LHC	2014–2021	14	1–2	300	
HL-LHC	2023–2030	14	5	3000	Luminosity leveling
HE-LHC	>2035	26–33	2	100–300 per year	dipole fields 16–20 T
V-LHC	>2035	42–100			new 80 km tunnel

Table 2. Overview of proposed electron–positron colliders.

Facility	Years	E_{cm} (GeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Int. luminosity (fb^{-1})	Tunnel length (km)
ILC 250	> 2025	250	0.75		
ILC 500		500	1.8		≈30
ILC 1000		1000			≈50
CLIC 500	> 2030	500	2.3 (1.3)[a]	500	≈13
CLIC 1400	> 2038	1400 (1500)[a]	3.2 (3.7)[a]	1500	≈27
CLIC 3000	> 2047	3000	5.9	2000	≈48
LEP3	> 2022	240	1	100/year and exp.	LEP/LHC
T-LEP		350	0.65		80 (ring)

[a] Different scenario.

3.2. Lepton colliders

Due to the clean experimental environment and the precise knowledge of the collision energy and the initial-state polarization, lepton colliders may provide measurements with precision otherwise not achievable. Several concepts for linear and circular electron–positron colliders are under study. For an overview of the main accelerator parameters of proposed electron–positron colliders see table 2.

Muon colliders and $\gamma\gamma$ colliders offer further options for future facilities and are also discussed in this section.

3.2.1. International linear collider. The physics case and the machine design of a linear e^+e^- collider is under study since more than 20 years. A full Technical Design Report (www.linearcollider.org/ILC/Publications/Technical-Design-Report) has been completed, which describes the facility in detail. The design of the ILC is based on 1.3 GHz superconducting cavities with an average gradient of 31.5 MV m^{-1}. The European XFEL accelerator under construction at DESY will use very similar cavities and after completion the number installed will correspond to approximately 5% of the ones required for the ILC. The baseline design of the ILC foresees a center-of-mass energy of 500 GeV (design luminosity of 1.8×10^{34} cm^{-2} s^{-1}), with a possible upgrade to 1 TeV. The length of the facility to achieve 500 GeV is about 30 km ($\sim$ 50 km for 1 TeV). As a response to the discovery of the Higgs boson the Japanese physics community has presented an initiative to host the ILC in Japan. The proposal is to built the ILC machine in stages starting with a low energy phase ($\sim$250 GeV) to study the new particle with high precision. In an optimistic scenario the construction could start in 2015. After a 7–10 year construction period, the ILC operation would be able to start in 2025.

3.2.2. Compact linear collider. The concept of the CLIC is based on a two-beam acceleration technique in which the short, high power RF pulses (12 GHz) are extracted from a drive beam running parallel to the main linear accelerator structures. The normal-conducting accelerator structures of the main linac would reach a gradient of 100 MV m^{-1} and thus limit the overall length of the machine. The key technologies of this concept have been addressed in experimental set-ups at KEK, SLAC and CERN. The Conceptual Design Reports (CDRs) for the machine and for physics and detectors have been published in 2012 [2, 3]. The CDRs describe the project in three possible stages for center-of-mass energies of 500 GeV, 1.4 TeV and 3 TeV. The integrated luminosity targets are 500 fb^{-1}, 1.5 ab^{-1} and 2 ab^{-1} for the three envisaged energies. The proposed program of CLIC corresponds to an operational lifetime of about 25 years.

Site studies have shown that CLIC could be constructed underground in the Geneva area. The length of the main tunnel is $\sim$ 13, $\sim$ 27 and $\sim$ 48 km for center-of-mass energies of 500 GeV, 1.4 TeV, 3 TeV, respectively. The time line for the CLIC project foresees a focused R&D program on the accelerator and the detectors in 2012–2016. Provided that sufficient resources are made available the project could advance in 2017–2022 with the finalization of all parameters, the verification of the drive beam and other systems, and the preparation for the industrial procurement of all components. The construction of stage one (500 GeV) could be accomplished in the years 2023–2030, with commissioning starting in 2030.

3.2.3. Circular e^+e^- *colliders.* Motivated by the discovery of the new boson with a rather low mass of 125 GeV/c^2 a revival of circular e^+e^- colliders took place. A preliminary study has been done for a circular e^+e^- collider operating close to the ZH threshold at a center-of-mass energy of 240 GeV. This storage ring, called LEP3, was proposed to be installed in the existing LHC tunnel [4] for concurrent or alternating operation with the LHC. A constant luminosity of 10^{34} cm^{-2} s^{-1} was predicted. Operating the machine in a first stage at a lower energy at about the Z resonance a luminosity of several 10^{35} cm^{-2} s^{-1} was predicted.

Perpetuating the concept of circular e^+e^- machines one might go further and consider to use a possible new 80 km tunnel first for an e^+e^- collider, before it is eventually used for a hadron machine. In such a tunnel an e^+e^- machine operating up to a center-of-mass energy of 350 GeV ($t\bar{t}$ threshold) may be conceived (Tripe-LEP, TLEP). The beam lifetime of such a machine would be only a few minutes. As a consequence the design requires the installation of two machines, a low-emittance collider ring operating at a constant beam energy and a second accelerating ring ramping from injection to collision energy every few minutes and toping up the beam in the collider ring. Information on this study can be found at http://tlep.web.cern.ch.

3.2.4. Muon colliders. The use of muons instead of electrons and positrons in a collider machine has many advantages [5]. Due to the larger masses of muons synchrotron radiation is strongly suppressed allowing the construction of much smaller facilities with a very small energy spread because of the reduced bremsstrahlung. From the physics point of view muon colliders have also advantages over e^+e^- colliders as the s-channel production (e.g. of the Higgs boson) is also enhanced by the factor $(m_\mu/m_e)^2 \sim 40\,000$. Multi-TeV muon colliders could therefore become a future facility of choice to study Terascale physics after LHC. The required R&D for the critical components, such as multi-megawatt proton beams, targets, and muon cooling is ongoing in several collaborations worldwide.

3.3. $\gamma\gamma$ colliders

The collisions of photons at high energy are regarded as adjuncts or by-products of linear e^+e^- colliders such as the ILC or CLIC. $\gamma\gamma$ colliders could, however, also be developed as Higgs factories. The advantage of a $\gamma\gamma$ Higgs factory is the lower beam energy of about 80 GeV required to produce a Higgs boson in the s-channel, and the fact that no positrons are needed, in contrast to an e^+e^- collider. The principle of a $\gamma\gamma$ collider is as follows. Electrons from a high energy electron beam interact with the light of a very intense laser beam producing the photon beam by Compton back-scattering.

Two concepts for a $\gamma\gamma$ collider have been proposed. CLICHE (CLIC Higgs experiment) [7] proposes to use a first full scale module of the CLIC test setup with electrons accelerated to 75 GeV interacting with photons from a powerful mercury laser system. Another proposal for a $\gamma\gamma$ collide is SAPPHiRE (small accelerator for photon–photon Higgs production using recirculating electrons) [6] based on a pair of $\sim$10 GeV recirculating electron linacs, similar in design to those proposed in the Large Hadron electron Collider (LHeC) project (see section 3.4). The electrons pass four times through two superconducting linacs acquiring about 80 GeV before they interact with the laser light. The target luminosity of SAPPHiRE is $\mathcal{L}_{ee} \sim 2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ resulting in $\mathcal{L}_{\gamma\gamma} \sim 3.6 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$ (for $E_{\gamma\gamma} \geqslant 0.6E_{CM}$). The laser system requires 1 TW peak power and 5 ps pulse length at a wavelength of 351 nm. The laser system is the issue of a $\gamma\gamma$ collider that requires intensive R&D.

3.4. Lepton–hadron colliders

The LHeC study group has published a CDR in 2012 [8]. The report describes in considerable detail the design of an electron or positron accelerator intercepting the proton or ion beam of LHC and the design of the experiment. The preferred design foresees two linacs each accelerating the beam by 10 GeV and by passing the beam three times through the structure the final energy of 60 GeV is reached and the beam is returned from the interaction point and decelerated for beam power recovery. The new tunnel must be arranged tangential to the LHC. It turns out that the only practicable solution for the interaction point for LHeC with the LHC is IP2 (ALICE), hence a transition from the ALICE experiment to the LHeC experiment would become mandatory. The LHeC is designed to run synchronously with the LHC. The target luminosity for e^-p is $10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$, whereas the e^+p luminosity will be about a factor 10 lower.

The LHeC could further become the first electron–ion (eA) collider and by back-scattering laser techniques a photon beam could be extracted to give access to γp and γA physics at high energies.

3.5. Long-baseline neutrino experiments

With the discovery of a large θ_{13} neutrino mixing angle in 2012 accelerator driven long-baseline experiments with conventional beams may have the discovery potential for CP violation in the neutrino sector and the required sensitivity to define the neutrino mass hierarchy. Several proposals for long-baseline experiments in Europe, in Japan, and in the US have been proposed. A very detailed summary of the physics potential of these projects is described in chapter 4 of the Briefing Book (http://europeanstrategygroup.web.cern.ch/europeanstrategygroup/Briefing_book.pdf).

4. Summary of the main points of the strategy update

The approved Update of the European Strategy contains 17 points, labeled (a)–(q). Each point is introduced by a statement followed by a recommendation.

Statements (a) and (b) are general issues commenting the fact that the European organizational model for particle physics has been very successful and effective and should thus be continued. The proof of it is the overwhelming success of the LHC. It is further noted that the scale of the facilities required for particle physics experiments results in a globalization of the field and that the European strategy is taking this into account.

Concerning the scientific activities the Strategy Update had to find a balance between maintaining the diversity of the scientific program and setting priorities since the available resources are limited. As a consequence the Strategy Update prioritizes only large scale projects and facilities of global and supra-regional dimension. Competitive small and medium size projects are seen important to keep the diversity of our field, because a breakthrough or hints to physics beyond the standard model may emerge in unexpected areas. The proposed large-scale projects and facilities, summarized in the previous chapter, were carefully analyzed in view of their physics case and the technological readiness. Finally the Strategy Update identified four activities (statements c–f) assigned to have the highest priority:

- The upgrade program of LHC toward high-luminosity with the aim to collect ten times the integrated luminosity of the initial design, i.e. $3\,\mathrm{ab}^{-1}$. The four large LHC experiments presented a convincing physics case for this project. This is a large new project for both the LHC machine and the experiments with many challenges ahead requiring a worldwide effort.
- Design studies and R&D for an ambitious post-LHC accelerator project at CERN. The decision for a future machine at CERN can only be taken once the physics results from LHC running at 14 TeV are available. At that time, probably in time for the next Update of the European Strategy, studies should be available in sufficient details on physics, technologies, and cost estimates for possible future machines. The Strategy Update sees CERN as the place for the energy frontier facilities and suggests vigorous R&D programs specifically on high-field magnets and high-gradient accelerating structures.
- European support for an ILC. There is a strong initiative from Japan to host the ILC with an initial center-of-mass energy of 250 GeV, operated as Higgs factory, and later to be upgraded to 350 and 500 GeV. The Strategy Update acknowledges the physics case of such a machine and suggest to look into a possible European participation.
- Participation in a long-baseline neutrino experiment. The recent developments in neutrino physics define a clear physics case for a long-baseline neutrino experiment. The Strategy Update propose to explore an European participation in such experiments in the US and Japan.

The statements (g)–(k) describe and support other scientific activities of the particle physics program in Europe which are important for the field: theory, which is among other things highly important to provide understanding of the results produced by the LHC experiments. Experiments studying quark flavor physics, lepton flavor violation and other precision measurements at lower energies (e.g. dipole moments, antiprotons, etc) are truly complementary to the experiments at the high energy frontier. Instrumentation, state-of-the-art infrastructure and large-scale data-intensive computing are mentioned as requirements for present and future high energy physics experiments. In the overlap of particle and astroparticle physics non-accelerator experiments, such as the search for the proton decay, the neutrinoless double beta decay and dark matter. A closer collaboration of CERN and the institutes working in the field of astroparticle physics is desirable to exploit synergies. At the CERN laboratory several unique experiments are performed in the field of nuclear physics, e.g. heavy ion experiments, nTOF, ISOLDE, etc. The strategy update supports these activities and the continuation of these facilities.

Organizational issues are addressed in statements (l) and (m). In the first of these statements the future role of CERN in a global particle physics facility in Europe but also elsewhere is discussed. The European strategy is to have CERN as the leading partner in such projects in order to maximize the European impact. The update statements also acknowledge the memorandum of understanding signed by CERN and the European Commission in view of the important participation in the European Research Area.

The wider impact of particle physics through public engagement and communication is also highlighted in the statements. The two networks EPPCN[5] and IPPOG[6] are mentioned and adequate funding for them is stipulated. Knowledge and technology transfer is a big issue for particle physics. To pursue the demanding basic research particle physics has developed accelerators, detectors and information technology which has found many applications outside our field. The HEPTech network has been created to coordinate and promote this activity. It is recommended to pursue and amplify these efforts. Education and training is another activity which is crucial for particle physics but also has a wide impact on society. People trained at CERN, in national laboratories and universities transfer their knowledge to industry and society.

In the concluding recommendations the Strategy Update supports periodic updates at intervals of about 5 years. The experience gained in this update process is throughout positive. Nevertheless, it is recommended to revisit the organizational framework in which the CERN Council is dealing with European strategy matters.

Appendix. The European strategy for particle physics—update 2013

Approved by CERN Council in a special meeting, Brussels, 30 May 2013

Preamble

Since the adoption of the European Strategy for Particle Physics in 2006, the field has made impressive progress in the pursuit of its core mission, elucidating the laws of nature at the most fundamental level. A giant leap, the discovery of the Higgs boson, has been accompanied by many experimental results confirming the Standard Model beyond the previously explored energy scales. These results raise further questions on the origin of elementary particle masses and on the role of the Higgs boson in the more fundamental theory underlying the Standard Model, which may involve additional particles to be discovered around the TeV scale. Significant progress is being made toward solving long-standing puzzles such as the matter–antimatter asymmetry of the Universe and the nature of the mysterious dark matter. The observation of a new type of neutrino oscillation has opened the way for future investigations of matter-antimatter asymmetry in the neutrino sector. Intriguing prospects are emerging for experiments at the overlap with astroparticle physics and cosmology. Against the backdrop of dramatic developments in our understanding of the science landscape, Europe is updating its strategy for particle physics in order to define the community's direction for the coming years and to prepare for the long-term future of the field.

[5] European Particle Physics Communication Network.
[6] International Particle Physics Outreach Group.

General issues

(a) The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN. *Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.*

(b) The scale of the facilities required by particle physics is resulting in the globalization of the field. *The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.*

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

(c) The discovery of the Higgs boson is the start of a major program of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade program will also provide further exciting opportunities for the study of flavor physics and the quark-gluon plasma.*

(d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton–proton and electron–positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D program, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

(e) There is a strong scientific case for an electron–positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. *Europe looks forward to a proposal from Japan to discuss a possible participation.*

(f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino program exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

Other scientific activities essential to the particle physics program

(g) Theory is a strong driver of particle physics and provides essential input to experiments, witness the major role played by theory in the recent discovery of the Higgs boson, from the foundations of the Standard Model to detailed calculations guiding the experimental searches. *Europe should support a diverse, vibrant theoretical physics program, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighboring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.*

(h) Experiments studying quark flavor physics, investigating dipole moments, searching for charged-lepton flavor violation and performing other precision measurements at lower energies, such as those with neutrons, muons and antiprotons, may give access to higher energy scales than direct particle production or put fundamental symmetries to the test. They can be based in national laboratories, with a moderate cost and smaller collaborations. *Experiments in Europe with unique reach should be supported, as well as participation in experiments in other regions of the world.*

(i) The success of particle physics experiments, such as those required for the high-luminosity LHC, relies on innovative instrumentation, state-of-the-art infrastructures and large-scale data-intensive computing. *Detector R&D programs should be supported strongly at CERN, national institutes, laboratories and universities. Infrastructure and engineering capabilities for the R&D program and construction of large detectors, as well as infrastructures for data analysis, data preservation and distributed data-intensive computing should be maintained and further developed.*

(j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field.*

(k) A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments. *The CERN Laboratory should maintain its* *capability to perform unique experiments. CERN should continue to work with NuPECC on topics of mutual interest*.

Organizational issues

(l) Future major facilities in Europe and elsewhere require collaboration on a global scale. *CERN should be the framework within which to organize a global particle physics accelerator project in Europe, and should also be the leading European partner in global particle physics accelerator projects elsewhere. Possible additional contributions to such projects from CERN's Member and Associate Member States in Europe should be coordinated with CERN.*

(m) A Memorandum of Understanding has been signed by CERN and the European Commission, and various cooperative activities are under way. Communication with the European Strategy Forum on Research Infrastructures (ESFRI) has led to agreement on the participation of CERN in the relevant ESFRI Strategy Working Group. The particle physics community has been actively involved in European Union framework programs. *CERN and the particle physics community should strengthen their relations with the European Commission in order to participate further in the development of the European Research Area.*

Wider impact of particle physics

(n) Sharing the excitement of scientific discoveries with the public is part of our duty as researchers. Many groups work enthusiastically in public engagement. They are assisted by a network of communication professionals (EPPCN) and an international outreach group (IPPOG). For example, they helped attract tremendous public attention and interest around the world at the start of the LHC and the discovery of the Higgs boson. *Outreach and communication in particle physics should receive adequate funding and be recognized as a central component of the scientific activity. EPPCN and IPPOG should both report regularly to the Council.*

(o) Knowledge and technology developed for particle physics research have made a lasting impact on society. These technologies are also being advanced by others leading to mutual benefits. Knowledge and technology transfer is strongly promoted in most countries. The HEPTech network has been created to coordinate and promote this activity, and to provide benefit to the European industries. *HEPTech should pursue and amplify its efforts and continue reporting regularly to the Council.*

(p) Particle physics research requires a wide range of skills and knowledge. Many young physicists, engineers and teachers are trained at CERN, in national laboratories and universities. They subsequently transfer their expertize to society and industry. Education and training in key technologies are also crucial for the needs of the field. *CERN, together with national funding agencies, institutes, laboratories and universities, should continue supporting and further develop coordinated programs for education and training.*

Concluding recommendations

(q) This is the first update of the European Strategy for Particle Physics. It was prepared by the European Strategy Group based on the scientific input from the Preparatory Group with the participation of representatives of the Candidate for Accession to Membership, the Associate Member States, the Observer States and other organizations. Such periodic updates at intervals of about five years are essential. *Updates should continue to be undertaken according to the principles applied on the present occasion. The organizational framework for the Council Sessions dealing with European Strategy matters and the mechanism for implementation and follow-up of the Strategy should be revisited in the light of the experience gained since 2006.*

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